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Interferometer system, method for recording an interferogram and method for providing and manufacturing an object having a target surface

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The present invention relates to an interferometer system and a method for recording an interferogram. The interferometer system and the method are preferably used to

15 determine topological properties of an object surface from the interferogram by evaluating the recorded interferogram.

Furthermore, the invention relates to a method for providing and manufacturing an object having a target

20 surface, wherein deviations between the target surface and an actual surface of the object are determined from an interferogram and wherein the object is provided or reworked dependent upon such deviations.

25 Usually, interferometer systems are used, among others, to determine topological properties of an object surface. To this end, for example, a known reference surface and an object surface to be measured are illuminated with coherent radiation, and an object wave field reflected from the

30 object surface and a reference wave field reflected from the reference surface are superimposed on e.g. a screen such that an interference pattern is generated thereon. From the interference pattern a difference between the optical paths from the reference surface to the screen and

35 from the object surface to the screen may be determined position-dependently. From such differences topological

differences between the object surface and the reference surface may then be determined.

Two techniques are commonly applied to determine such path differences with an interferometer system:

A first approach is the so-called fringe pattern interferometery "FPI", wherein an optical path difference between two wavefronts is determined from positions of fringe centers of an interference pattern. In this respect, reference can be made, for example, to R.A. Jones and P.L. Kadakia, "An Automated Interferogram Technique", Applied Optics, vol. 7, pp. 1477-1482 (1968); Zanoni, U.S. patent no. 4,159,522, published June 26, 1979 and Zanoni, U.S. patent no. 4,169,980, published October 2, 1979.

Another approach is the so-called phase measuring interferometry "PMI", wherein the phase difference between the two wavefronts is calculated for each pixel of a detector from a plurality of interference patterns, said plurality of interference patterns being recorded in that different phase differences are generated therein. In this respect, reference can be made, for example, to J.H. Brunning et al., "Digital Wavefront Measuring Interferometer for Testing Optical Surfaces and Lenses", Applied Optics, vol. 13, pp. 2693-2703 (1974); Gallagher et al., U.S. patent no. 3,694,088, published September 26, 1972, N. Balasubramanian, U.S. patent no. 4,225,240, published September 30, 1980; M. Schaham, Proceedings SPIE, vol. 306, pp. 183-191 (1981); and H.Z. Hu, "Polarization heterodyne interferometry using a simple rotating analyzer. 1: Theory and error analysis", Applied Optics, vol. 22, pp. 2052-2056 (1983).

From US patent 4,594,003 there is known an interferometer system in which the frequency of the radiation source is

variable so that the fringes of the interference pattern can be displaced without an optical component of the interferometer system, such as a reference surface or an object surface, having to be mechanically shifted. In said system, it is provided for a change over such a range that the fringes of the interference pattern are displaceable over a full fringe width. Four interference patterns are recorded, namely with four different frequencies of the radiation source distributed within said range. For each pixel of the detector a phase φ of the optical path difference is then calculated according to the following formula:

$$\varphi(x,y) = \arctan\left(\frac{B(0) - B(2)}{B(1) - B(3)}\right),$$

wherein B(0) to B(3) are the intensities of the individual images at the respective pixel.

This known method for determining path differences is less suitable if there is a further surface present in the interferometer system which likewise reflects a wave field which interferes with the wave fields reflected by the reference surface and the object surface. The resulting interference pattern is then of a particular complex nature. This situation occurs, for example, if a surface of a transparent plate with two substantially plane-parallel surfaces is to be measured.

It is an object of the present invention to provide an interferometer system and a method for recording an interferogram which is less sensitive to disturbing reflections.

Moreover, it is an object of the invention to provide a method for providing and manufacturing an object with a target surface.

In this respect, the invention proceeds from an interferometer system comprising a reference surface, an object surface, a radiation source for illuminating the reference surface and the object surface with radiation of an adjustable frequency and a position-sensitive radiation detector. The radiation source, the reference surface, the object surface and the detector are disposed such that a reference wave field reflected from the reference surface is superimposed with an object wave field reflected from the object surface to form an interference pattern with a position-dependent intensity distribution, said interference pattern being imaged onto the detector. Here, the interference pattern formed by superposition of the reference wave field and the object wave field is disturbed by a disturbing wave field which is likewise superimposed on said wave fields, said disturbing wave field being reflected from a disturbing interference surface which is illuminated by the radiation source together with the reference surface and the object surface, respectively.

The invention is distinguished in this respect by an integrator for position-dependent averaging of a plurality of interference patterns which are recorded at different frequencies of the radiation emitted by the radiation source.

The resulting interferogram is thus generated such that for each position of the interferogram an average is formed from the intensities of the individual interference patterns at said position. Herein, the averaging is preferably a weighted averaging.

The weighting factors for the weighted averaging or/and the values of the different radiation frequencies are preferably set as a function of the distance of the

disturbing interference surface from the object surface and the reference surface, respectively. Preferably, these values are set such that an influence of the disturbing wavefront on the interferogram is substantially averaged out. The interferogram formed by averaging a plurality of interference patterns is then of such a configuration and intensity distribution, respectively, which corresponds approximately to that which would be generated by the wavefronts reflected from the object surface and the reference surface alone as if the disturbing interference surface were not present in the interferometer system.

In this respect, it is further advantageous for the optical path difference between the reference surface and the object surface to be adjustable, since by appropriately selecting these distances relative to each other, an influence of the disturbing wavefront on the interferogram can be further reduced.

It is advantageous for the plurality of frequencies for producing the plurality of interference patterns to be adjusted successively in time over a period of time which corresponds to an exposure time interval of a camera which records the interference patterns. This enables a particular simple design of the integrator since it is then formed by the camera itself.

Embodiments of the invention will be illustrated with reference to drawings below, wherein

Figure 1   is an embodiment of an interferometer system according to the invention,

Figure 2   is a diagram illustrating differing frequencies of radiation emitted by a radiation source of figure 1 for generating interference patterns,

Figure 3   shows a time dependency of the radiation emitted
            from the radiation source of figure 1,

Figure 4   is a diagram showing an interferogram intensity
            as a function of an optical path difference for
            an interference pattern generated by the
            interferometer system of figure 1 when the
            frequencies are set in accordance with figures 2
            and 3,

Figure 5   shows an interferogram modulation as a function
            of an optical path difference in the
            interferometer system of figure 1 which results
            from another time-dependent setting of the
            frequencies of the radiation source,

Figure 6   shows a frequency distribution corresponding to
            figure 2 of the radiation emitted from the
            radiation source,

Figure 7   is a representation corresponding to figure 4 of
            the interferogram intensity as a function of the
            optical path length difference when using the
            frequency distribution shown in figure 6,

Figure 8   is a partial view of a further embodiment of the
            interferometer system according to the invention,
            and

Figure 9   is a partial view of a further embodiment of the
            interferometer system according to the invention.

Figure 1   shows a Fizeau interferometer system 1 for
measuring a surface 5 of a plane-parallel plate 3. The

plate 3 is fixed in a support 4 which is displaceable relative to a reference surface 23 by means of a motor drive 6.

5   The interferometer system 1 comprises a light source 9 which emits a beam 11 of coherent light with adjustable wavelength and frequency, respectively. The light source 9 is a so-called ECDL source, i.e., a diode laser with adjustable external cavity (external cavity diode laser).

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Such an ECDL radiation source is, for example, described in the article "Widely Tunable External Cavity Diode Lasers" by Tim Day, Michael Brownell and I-Fan Wu. Corresponding sources can be obtained from the company New Focus, Inc.,

15   1275 Reamwood Avenue, Sunnyvale, CA 94089, USA.

The beam 11 emitted by the source 9 is focused by a lens 13 onto a rotating ground glass plate or diffusing plate 15 for suppressing spatial coherence of the radiation. The

20   diffusing plate 15 rotates about an axis of rotation not shown in figure 1.

After having passed through the focus in the region of the diffusing plate 15, the expanding beam 11' traverses a

25   semi-transparent mirror 17 and, after having been sufficiently expanded, is then rendered parallel by a collimator 19 which may comprise one or more lenses. The thus prallelized beam 11" passes through a glass plate 21 whose surface 23 facing away from the collimator 19 forms

30   the reference surface for measuring the surface 5 of the plane-parallel plate 3. The reference surface 23 is provided as flat as possible. A surface 25 of the plate 21 facing towards the collimator 19 extends at an angle with respect to the reference surface 23 so that radiation

35   reflected from said surface 25 is not reflected back upon itself and does not contribute to disturbing interferences.

Radiation reflected back upon itself from reference surface
23 is again collimated by the collimator 19, impinges on
the semi-transparent mirror 17 and is imaged by the mirror,
5   after having passed through an aperture 27 and an ocular
29, onto a radiation-sensitive layer 31 of a CCD camera 33.
A part of the beam 11 passing through the reference surface
23 impinges on the surface 5 of the plane-parallel plate 3
to be measured. The surface 5 to be measured is oriented as
10   orthogonally as possible in respect of the direction of the
parallel beam 11". A portion of the radiation impinging on
the surface 5 to be measured is, again, reflected back upon
itself, passes again through the plate 21 and is likewise
focused by the collimator 19 and imaged on the radiation-
15   sensitive surface 31. The radiation-sensitive layer 31 of
the camera 33 thus forms a screen on which the radiation
reflected back from the reference surface 23 interferes
with the radiation reflected from the surface 5 to be
measured.

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It is one purpose of the interferometer arrangement 1 to
detect the interference pattern generated by the
interfering superposition of the radiation reflected back
from the reference surface 23 and the radiation reflected
25   back from the surface 5 to be measured.

As already mentioned above, the plate 3 is, however, a
plane-parallel plate, that is, the surface 5 of the plate 3
to be measured and a back surface 7 of the plate 3 opposed
30   thereto extend substantially parallel to each other. This
results in that a portion of the radiation 11 passing
through the surface 5 to be measured is likewise reflected
back upon itself from the back surface 7 of the plate 3 and
imaged on the radiation-sensitive layer 31.

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Accordingly, on the one hand, the radiation reflected back from the reference surface 13 interferes on the radiation-sensitive layer 31 with the radiation reflected back from the surface 5 to be measured, an optical path length difference therebetween being $2 \cdot c_0$, and, on the other hand, the radiation reflected from the reference surface 23 interferes on the radiation-sensitive layer 31 with the radiation reflected from the back surface 7 of the plane-parallel plate 3, an optical path length difference therebetween being $2 \cdot c_2$, and, furthermore, the radiation reflected from the surface 5 of the plate 3 to be measured interferes there with the radiation reflected from the back surface 7 thereof, an optical path length difference therebetween being $2 \cdot c_1$. The interference pattern generated on the radiation-sensitive layer 31 is thus very complicated and difficult to evaluate.

The camera 33 supplies the data which are representative of a radiation intensity distribution on the radiation-sensitive surface 31 via a data line 35 to a computer 37. The computer 37, in turn, generates a representation of the interference pattern on the radiation-sensitive layer 31 on a display 39, an interference pattern being represented merely schematically in figure 1 by a plurality of fringes 40. Further, the computer 37 stores the data and also performs an evaluation of the interference pattern to determine therefrom level differences between the reference surface 23 and the surface 5, to be measured, and the topology of the surface 5 to be measured, respectively.

Moreover, the interferometer system 1 comprises a controller 41 which is supplied, via a control line 43, with frequency data and which is triggered by the computer 37, said controller then setting, time-dependently, via a line 45 the frequency of the radiation 11 to be emitted from the source 9 in response to a trigger signal 48

generated by the camera 33 which is also supplied to the computer via a line 47.

A method for operating the interferometer system 1 is
5   described hereinbelow, the plate 3 being assumed to have a thickness of 74 mm, so that, taking the refractive index of the glass of the plate 3 into consideration, a resulting optical path difference $2 \cdot C_1$ of 214.39 mm is provided.

10   First, the controller 41 sets, via line 45, the frequency of the radiation source 9 to a first frequency with a value $f - \Delta f$ and starts, via line 47, the integration of the CCD camera 33 so that the interference pattern which is generated by the wavefronts reflected from the three
15   surfaces 23, 5 and 7, upon illumination with radiation of the frequency $f - \Delta f$, impinges on the radiation-sensitive surface 31 of the camera 33, and the corresponding radiation intensity is integrated there. After 3.75 msec, the controller 41 sets the source 9 to a second, higher
20   frequency f so that interference patterns generated at this frequency impinge during the integration time of the camera 33 as second interference patterns on the radiation-sensitive layer 31, and the corresponding radiation intensities are integrated there with the intensities of
25   the first interference pattern. After a further 7.5 msec, the controller 41 sets the frequency of the radiation source 9 to a still higher, third frequency with the value $f + \Delta f$ so that the interference pattern generated at this third frequency likewise impinges during the integration
30   time of the camera on the light-collecting surface 31 thereof, and the intensities of the third interference pattern are added to the intensities of the first and the second interference patterns. The illumination with the third frequency $f + \Delta f$ lasts for 3.75 sec. After that, the
35   controller 41 causes, via line 47, the integration time of the camera 33 to terminate, and the data which represent

position-dependently the entire light intensity which has impinged during the integration time on the light-collecting surface 31 are read-out and supplied to the computer 37 via line 35.

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The above-described integration time of the camera of 15 msec was chosen in the present embodiment to achieve a high-quality image at the given laser power.

10 Depending on the laser energy available and other boundary conditions, it is also possible to set different integration times.

These data are thus representative of the sum of three
15 different inference patterns, wherein the first interference pattern was recorded with radiation of the frequency $f-\Delta f$, wherein the second interference pattern was recorded with the frequency f and wherein the third interference pattern was recorded with the frequency $f+\Delta f$.
20 When the three interference patterns are integrated, the interference pattern recorded at the medium frequency f is weighted with double the weighting factor as compared to the two other frequencies $f-\Delta f$, $f+\Delta f$.

25 This weighted illumination with three different frequencies is again illustrated in figures 2 and 3. In figure 2, the spectral power density is shown in arbitrary units as a function of the wave number k of the radiation of the source 9. It is apparent that the illumination with the
30 three different frequencies is effected with the relative weighting factors 0.5, 1 and 0.5. This spectral power density distribution can be represented as a formula as follows:

$$F(k) = A \cdot \left[\frac{1}{2} \delta\big(k - (k_0 - \Delta k)\big) + \delta\big(k - k_0\big) + \frac{1}{2} \delta\big(k - (k_0 + \Delta k)\big) \right]$$

Equation (1)

wherein

δ is Dirac's delta function

k   is the wave number $2\pi/\lambda$,

k_0 is the basic wave number $2\pi/\lambda_0$ and

Δk is the wave number change corresponding to the frequency change Δf.

In the present case, λ_0 was chosen to be 632.8 nm. The radiation source 9 can be set to this wavelength, and this setting is advantageous in so far as, apart from the radiation source, a structure and components which are known from interferometers operated with conventional He-Ne lasers can be used for the interferometer system.

The interferogram as Fourier transform of the spectral density may be written as

$$I(x) = \int_0^\infty F(k) \cdot \cos kx \cdot dx = A \cdot \frac{1}{2}\{\cos(k_0 - \Delta k) \cdot x + \cos(k_0 + \Delta k) \cdot x\} + A \cdot \cos(k_0 x)$$

$$= A \cdot \cos k_0 x \cdot (1 + \cos \Delta kx)$$

Equation (2)

Accordingly, a beat wave number of Δk results for the interferogram. A graph of the function I(x) is schematically shown in figure 4 for an arbitrary point in the interferogram. An envelope of the depicted curves is also referred to as interference contrast or modulation. Accordingly, the modulation periodically increases and decreases as a function of the distance from the reference

surface, wherein the modulation goes down to zero at specific distances.

An advantageous operation of the interferometer system 1 is provided when the reflecting surfaces 23, 5, 7 are disposed relative to one another such that the optical path difference $2 \cdot C_1$ caused by the distance between the surface 5 to be measured and the back surface 7 approximately coincides with the first minimum of the modulation minimum, and such the path difference $2 \cdot C_2$ caused by the distance between the reference surface 23 and the back surface 7 of the plate 3 approximately coincides with the second minimum of the modulation minimum, and such that the path length difference C_0 produced by the distance between the reference surface 23 and the surface 5 to be measured approximately coincides with the second maximum of the modulation maximum. To this end, first of all the frequency change Δf and wave number change Δk, respectively, are determined as follows:

First, $1+\cos\Delta k \cdot C_1$ is set to 0, which results in $\Delta k \cdot C_1 = \pi$. As, in the present example, the plate thickness C_1 is assumed to be 214.139 mm, this results in $\Delta k = 14.67 m^{-1}$. Then, the distance of the plate 3 from the reference surface 23 is adjusted via the drive 6 such that $\Delta k \cdot C_2 = 3\pi$ is fulfilled. It should be noted in this respect that the last-mentioned condition need to be observed only with relative little accuracy, since the modulation according to figure 4 exhibits quadratic minima and these are thus relatively insensitive to changes in the optical path difference.

With the above-illustrated setting of Δk and the distance of the back surface 7 from the reference surface 23, the optical path length difference $2 \cdot C_0$ is automatically set to such a value that it approximately coincides with the

second maximum of the modulation maximum according to figure 4.

Accordingly, the disturbing interferences caused by the back surface 7 of the plate 3 are thus effectively averaged out by the weighted averaging carried out during the integration time of the camera 33, so that the interferogram obtained by the averaging comprises, apart from a constant radiation portion, merely a fringe pattern as it would be generated by the interference solely of the wavefront reflected back from the reference surface 23 with the wavefront reflected back from the surface 5 to be measured. This relatively simple and undisturbed interference pattern is then subjected to a conventional evaluation method for fringe patterns in order to determine on the basis thereof the topology of the surface 5 to be measured.

The operation of the interferometer system 1 is not limited to control the frequency of the radiation source 9 with the timing scheme shown in figure 3. In the following, there is discussed as a variant the possibility to change the frequency of the radiation source 9 with a sinusoidal time dependency. First, be it assumed here for the interferogram intensity I:

$$I(x) = I_0 \cdot [1 + V \cdot \cos(k \cdot x - \Phi_0)],$$

Equation (3)

wherein

k   is the wave number of the radiation which can be assumed to be approximately constant in this formula,

x   is the optical wavelength difference,

Φ_0 is an interferogram phase and

V   is an interference contrast.

Due to the sinusoidal frequency change, the interferogram phase then results into

$$\Phi_0 = \Phi_0(t) = \Phi_0' + A \cdot \sin \omega t \; ,$$

<div align="right">Equation (4)</div>

wherein

Φ_0' is an average phase value,
ω is the angular velocity of the phase modulation and
A is a phase modulation amplitude.

Inserted into equation (3), it thus follows:

$$I(x,t) = I_0 \cdot \left[1 + V \cdot \cos\left(k \cdot x - \Phi_0' - A \cdot \sin \omega t \right) \right] .$$

<div align="right">Equation (5)</div>

The modulation period for the frequency change of the radiation is then set such that an integer numbered multiplicity thereof corresponds to the integration time of the camera 33. The time averaged interferogram is thus calculated to be

$$\bar{I}(x) = \frac{1}{2\pi} \int_{-\pi}^{\pi} I_0 \cdot \left[1 + V \cdot \cos\left(k \cdot x - \Phi_0' - A \cdot \sin \omega t \right) \right] \cdot d(\omega t)$$

$$= I_0 + I_0 \cdot V \cdot \cos\left(k \cdot x - \Phi_0' \right) \cdot \underbrace{\frac{1}{2\pi} \int_{-\pi}^{\pi} \cos\left(A \cdot \sin \omega a t \right) \cdot d(\omega t)}_{J_0(A)}$$

$$+ I_0 \cdot V \cdot \sin\left(k \cdot x - \Phi_0' \right) \cdot \underbrace{\frac{1}{2\pi} \int_{-\pi}^{\pi} \sin\left(A \cdot \sin \omega t \right) \cdot d(\omega t)}_{0}$$

$$\bar{I}(x) = I_0 \cdot \left[1 + V \cdot \cos\left(k \cdot x - \Phi_0' \right) \cdot J_0(A) \right]$$

<div align="right">Equation (6)</div>

wherein $J_0(A)$ is the Bessel function of Zero order of the phase modulation amplitude A. This function is shown in figure 5.

Phase modulation amplitudes A may then be determined such that interferences between the wavefronts reflected back from the surface 5 to be measured and from the back surface 7 of the plate 3 will disappear. Accordingly, the frequency modulation amplitude of the radiation source 9 must be set such that the phase modulation for the optical wavelength difference $2 \cdot C_1$ corresponds to the first Zero point of the Bessel function of Equation (6). This is the case for $A_1 = 0.76547 \cdot \pi$.

Furthermore, by changing the distance between the reference surface 23 and the plate 3, it is achieved that the optical wavelength difference $2 \cdot C_2$ corresponds to the second minimum of the Bessel function of Equation (6), which is the case for $A_2 = 1.7571 \cdot \pi$. The ratio of the optical path differences is thus given by the two first Zero point of the Bessel function $J_0(A)$

$$\frac{C_2}{C_1} = \frac{A_2}{A_1} = 2,2955$$

Equation (7)

On the other hand, $C_0 = C_2 - C_1$ is valid, and for the optical path difference C_0 to be measured, the amplitude results in

$$A_0 = \frac{C_0}{C_1} \cdot A_1 = \frac{C_2 - C_1}{C_1} \cdot A_1 = 0,9916 \cdot \pi$$

Equation (8)

At this point, the Bessel function J₀(A) has the value

$$J_0(A_0) = -0,297 \approx -0,3$$

Equation (9).

In this arrangement, three partial beams having an approximately identical basic intensity interfere with each other. However, only the fringe patterns of two interfering partial beams are visible in the weighted averaged, respectively integrated interferogram. The other interferences are averaged out, form a constant radiation portion which reduces the contrast, however. The effective contrast is calculated to be

$$V_{eff} = V \cdot J_0(A_0) = \frac{2}{3} \cdot |-0,3| = 0,2$$

Equation (10)

This contrast is sufficient to determine the positions of the fringes 40 and to be able to derive the topology of the surface 5 to be measured from the evaluation of the fringe pattern. However, it should be noted that the radiation frequency setting according to the scheme shown in figure 3 results in a higher effective contrast.

In the following, there is described as further exemplary embodiment for a situation such that the radiation source 9 is controlled to emit a Gaussian spectral power density as shown in figure 6

$$A(k) = \sqrt{\frac{\pi}{2}} \cdot \sigma \cdot e^{-\frac{(k-k_0)^2 \cdot \sigma^2}{2}} \quad ,$$

Equation (11)

wherein

k   is the wave number $2\pi/\lambda$

k_0 is the central wave number $2\pi/\lambda_0$

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σ   is the width of the Gaussian function.

For this spectral distribution a time-dependent control function for the radiation frequency is now to be

10 determined. In this respect, the dependency

$$\frac{dk(t)}{dt} = \frac{1}{A[k(t)]}$$

Equation (12)

15

is to be observed. This equation may be solved numerically by the computer 37 in order to finally obtain a time scheme corresponding to figure 3 for the controlling of the radiation frequency.

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With the spectral power density according to figure 6, a dependency of the interferogram intensity on the path difference results as it is shown in figure 7. It is evident therefrom that, at small distances from the

25 reference surface 23, high interference contrasts are achievable, whereas the contrast is strongly reduced at larger distances from the reference surface 23. This reduction in contrast is so strong that, when the plate 3 is positioned closely adjacent to the reference surface 23,

30 interferences which are caused by the back surface 7 are largely averaged out, and merely interferences caused by the surface 5 to be measured contribute to the fringe pattern of the averaged interferogram.

This corresponds to an interferogram with a radiation having a frequency which is constant in time and to a reduced coherence length which is shorter than the optical thickness C_1 of the plate 3. The time-dependent frequency change of a radiation source having a large coherence length thus has an effect which corresponds to a reduction of the time coherence for specific lengths. With reference to figure 4, this means that the time-dependent frequency change has caused the coherence of the radiation to be destroyed in the regions of the minima of the modulation minima.

Further variants of the embodiments illustrated with reference to figures 1 to 7 will be described hereinbelow. Components which correspond in their structure and function to those of figures 1 to 7 are designated by the same reference numbers, but, for the purpose of distinction, are supplemented by an additional letter. For the purpose of illustration, reference is made in each case to the entire foregoing description.

Figure 8 shows a partial view of an interferometer system 1a which is similar in construction to the interferometer system shown in figure 1. However, the interferometer system 1a serves to measure a concentric meniscus lens 3a rather than a plane-parallel plate. An aplanar collimator 51 having a plurality of lenses 52 to 56 is positioned in the beam path downstream of a reference plate 21a having a reference surface 23a, said collimator focussing the parallel radiation 11"a in a location 57 which further is a center of curvatures of the surfaces 5a and 7a of the concentric meniscus lens 3a.

Otherwise, the interferometer system 1a corresponds to the interferometer system shown in figure 1 and is operated according to a method as illustrated with reference to the

interferometer system of figure 1. That is, the frequency of the radiation source is controlled in a time-dependent manner such that disturbing interferences are largely averaged out in terms of time which disturbing interferences may be caused by a surface of the concentric meniscus lens 3a which is currently not measured, in particular the surface 7a, or by other optically effective components in the beam path.

The surfaces 5a and 7a of the meniscus lens 3a can also be measured by positioning the lens reversely, that is, it is positioned in the beam path with its convex surface 7a disposed towards the collimator 51 and upstream of the focus 57.

Figure 9 shows a variant of the interferometer system shown in figure 8. In contrast to that system, in the interferometer system 1b according to figure 9 a reference surface 23a is not provided on a separate reference plate but on a precisely fabricated surface of the lens 56b of an aplanar collimator 51, which surface is disposed towards the object to be measured. The interferometer system 1b, too, serves to measure a concentric meniscus lens.

Apart from the above-described time-dependencies of the frequency of the radiation source for generating the interferogram, it is also possible to select other time-dependencies which are found to be favorable. What is decisive in this respect is that interference effects which are caused by surfaces which are not to be measured are at least partially averaged out over time.

The interferometer system was described above as a Fizeau interferometer. However, it is also possible to use alternative interferometer types, such as a Michelson

interferometer configuration or a Twyman Green interferometer configuration.

In the above-described exemplary embodiments, the CCD camera was used as integrator for the weighted averaging of the interference patterns generated at different illumination frequencies. However, it is also possible to use other camera types which have an integration time which is adapted to the sequence of the illumination frequencies adjusted successively in time. Furthermore, it is possible to generate separate camera images for several radiation frequencies, to supply the same to the computer and to carry out the integration and weighted averaging, respectively, pixel-by-pixel in the computer. The term pixel should be understood within the scope of the present application to mean a resolution unit of the digitalized interference image which is determined, among others, by the camera system. Here, the averaging effected in the computer can also be carried out for groups of pixels, that is, with a resolution which is lower than the camera resolution.

The above-described interferometer system and the method for recording the interferogram is advantageously used in a method for providing an object and in a method for manufacturing an object with a predetermined target surface.

If, for example, the plane-parallel plate described with reference to figure 1 is to be manufactured with high precision, it is positioned in the beam path of the interferometer system, and an interferogram is recorded according to the above-described method. Deviations of the surface 5 from the flat nominal shape are determined from the interferogram. On the basis of these deviations, a reworking operation is planned. In particular, positions on

the surface 5 are determined from these deviations where a reworking operation, in particular, by further removal of material, is to be effected. After the reworking operation has been carried out, another interferogram is taken, if

5 required, and further reworking operations are effected, if required. If the recorded interferogram shows that deviations between the shape of the surface 5 and the plane nominal shape are less than a predefined value, the plate is provided and shipped.

10

This providing and manufacturing method can be applied to any other object which is to have a predetermined surface. The application to a concentric meniscus lens has already been described above. However, other applications for any

15 other objects are conceivable as well.
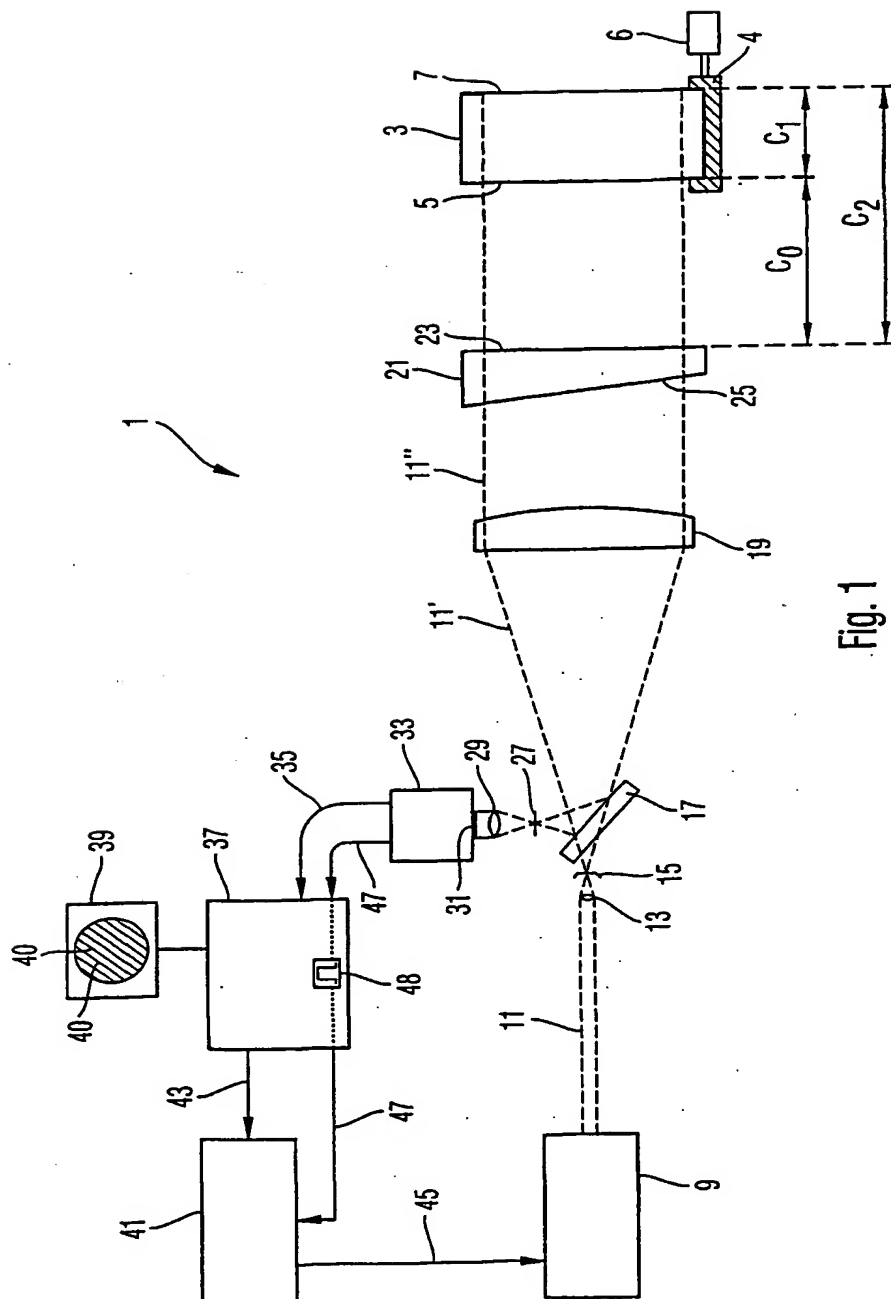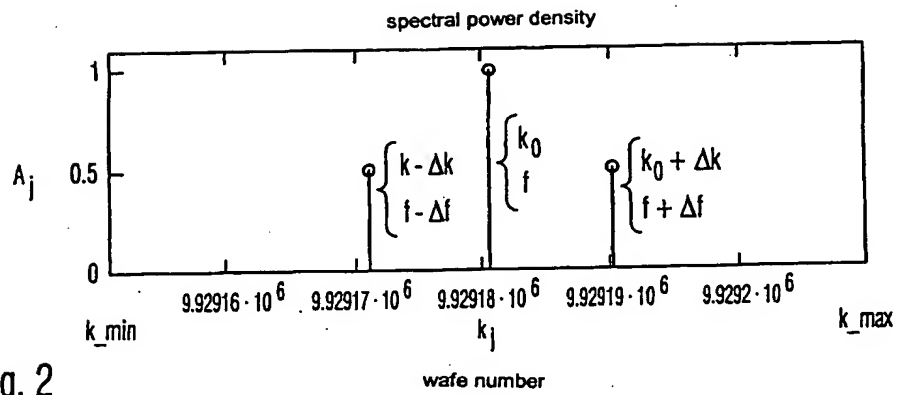
Fig. 1

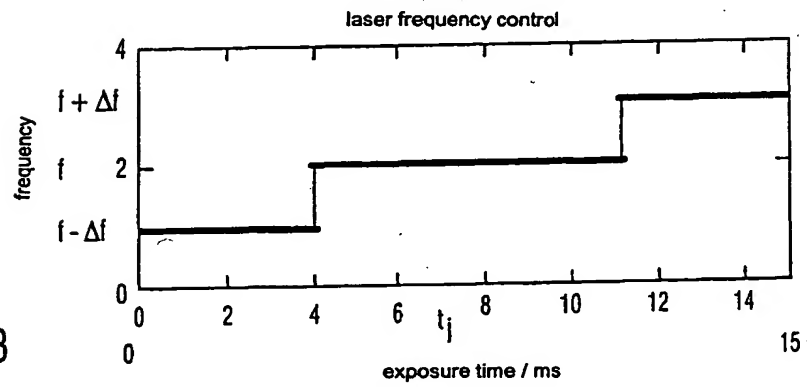**spectral power density**
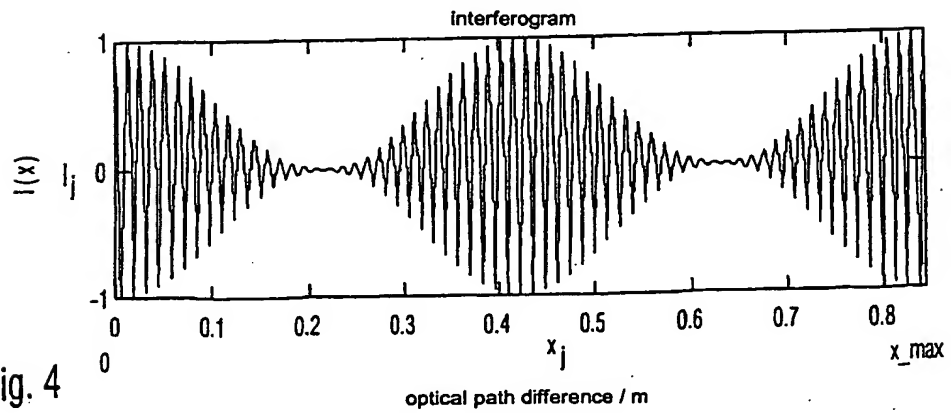

Fig. 2

laser frequency control

Fig. 3

interferogram

Fig. 4

Fig. 5

Bessel function of 0th order

Fig. 6

spectral power density distribution

Fig. 7

interferogram

distance from Fizeau surface
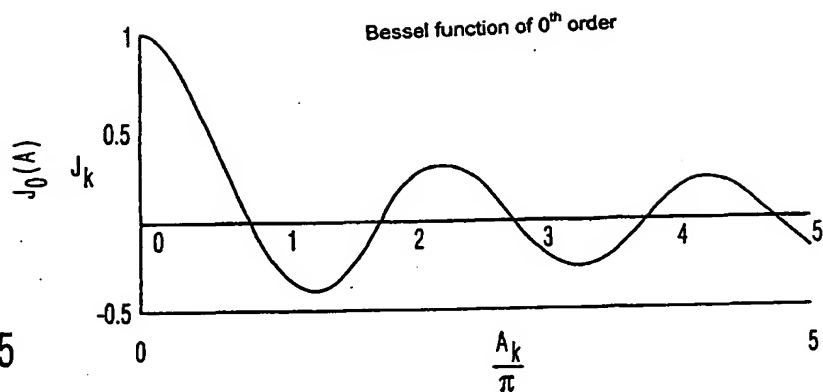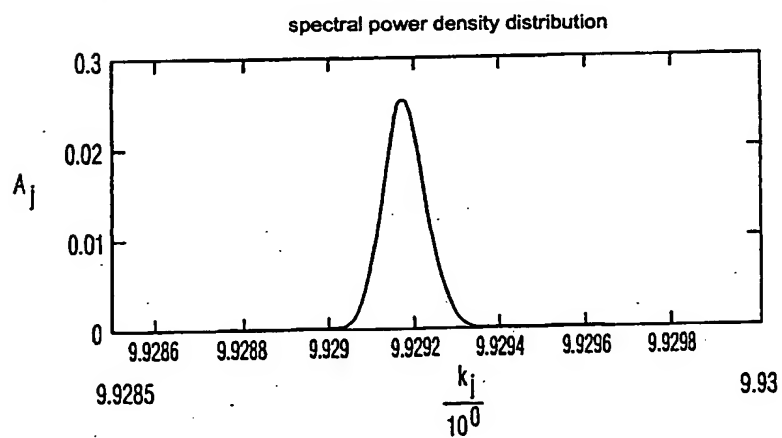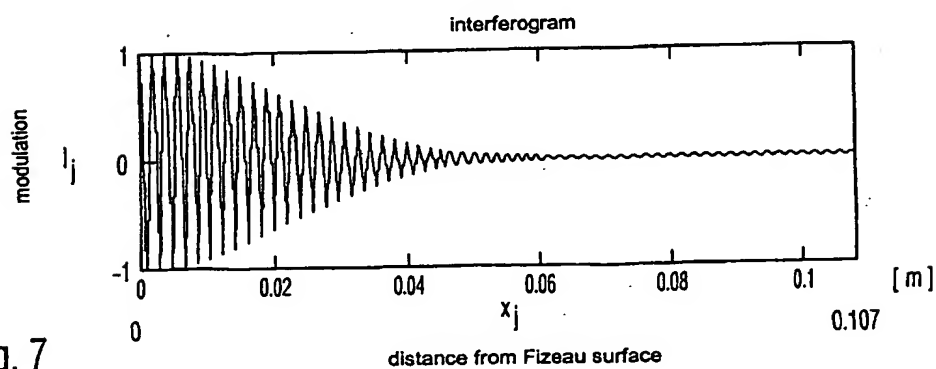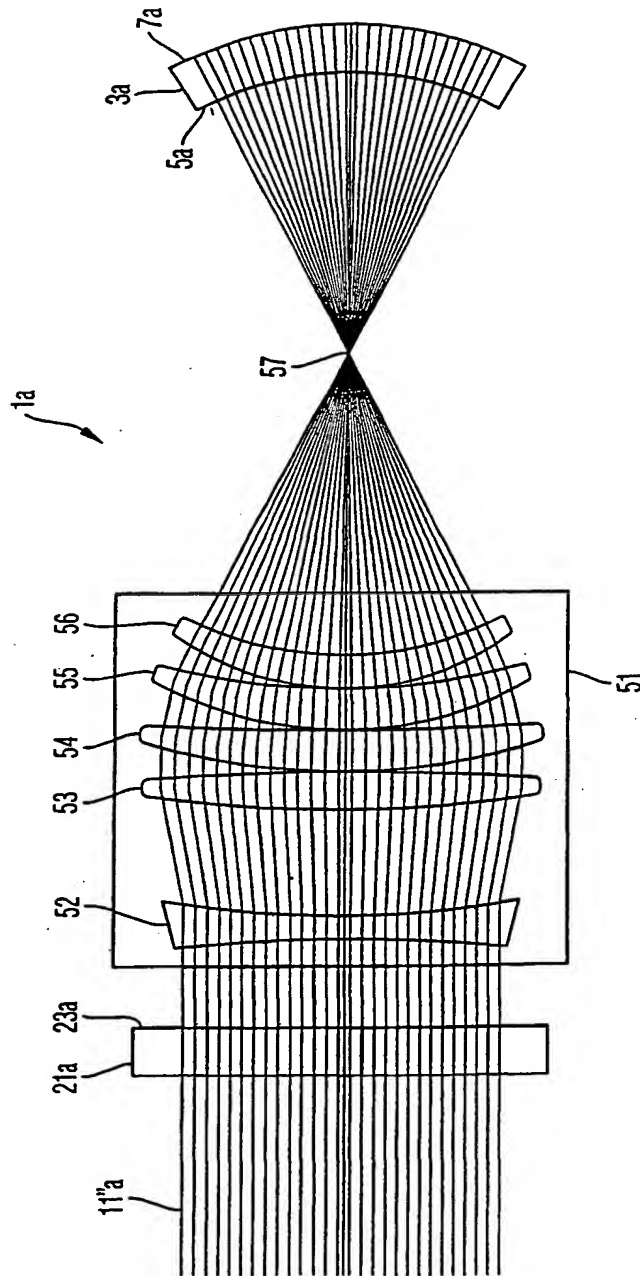
Fig. 8
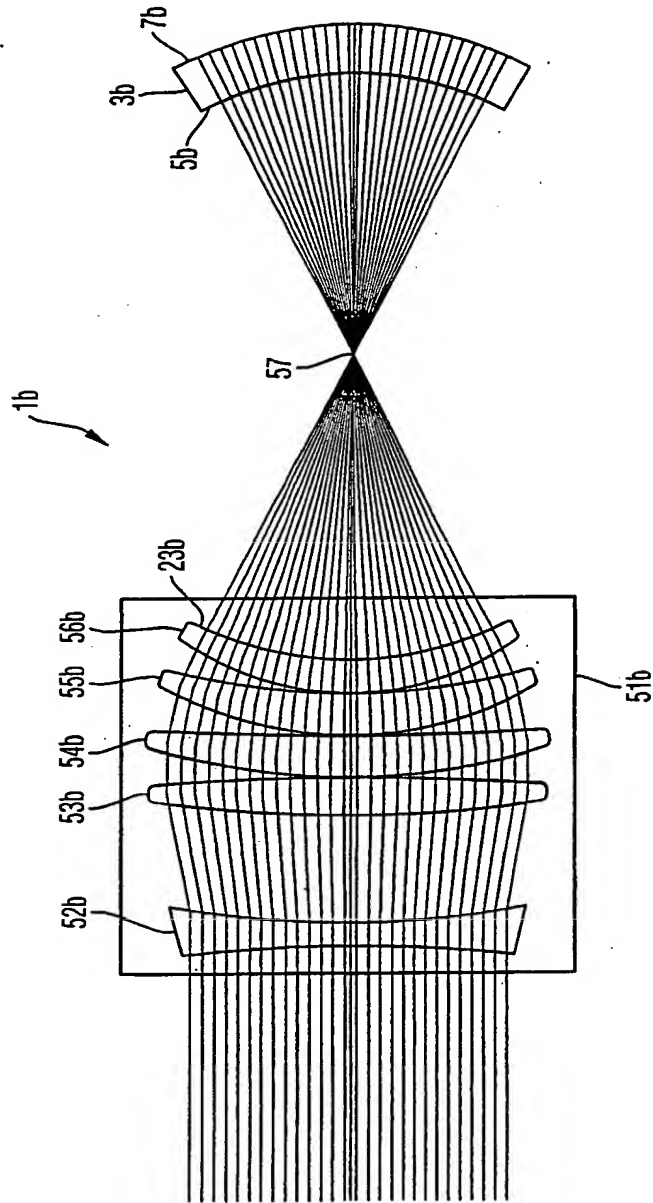
Fig. 9

Claims

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1.   A method for calibrating an interferometer optics for measuring optical surfaces, said method comprising:

10   arranging a first substrate having a first surface and a second surface opposite said first surface in a beam path of a first incident beam provided by said interferometer optics with said first surface facing towards said first incident beam,

15   and interferometrically taking a first measurement of first wave fronts generated by reflecting said first incident beam from said second surface of said first substrate;

20   arranging said first substrate in said beam path of said first incident beam with said second surface facing towards said first incident beam, and interferometrically taking a second measurement of second wave fronts generated by

25   reflecting said first incident beam from said second surface of said first substrate;

arranging a third surface of a second substrate in a beam path of a second incident beam, and

30   interferometrically taking a third measurement of third wave fronts generated by reflecting said second incident beam from said third surface of said second substrate, while said first substrate

is not arranged in said beam path of said second incident beam;

arranging said third surface of said second substrate and said first substrate in said beam path of said second incident beam, and interferometrically taking a fourth measurement of fourth wave fronts generated by reflecting said second incident beam from said third surface and through said first substrate; and

determining optical properties of said interferometer optics in dependence of said first, second, third and fourth measurements.

2. The method according to claim 1, wherein said second incident beam is provided by said interferometer optics.

3. The method according to claim 1, wherein said first and second surfaces of said first substrate and said third surface of said second substrate are substantially flat surfaces and wherein light of said first and second incident beams has substantially flat wave fronts.

4. The method according to claim 1, wherein said first and second surfaces of said first substrate and said third surface of said second substrate are substantially spherical surfaces and wherein light of said first and second incident beams has substantially spherical wave fronts.

5. The method according to claim 1, wherein said first substrate is of a wedge shape.

6. The method according to claim 1, wherein said interferometer has an optical axis and wherein said optical properties are rotationally symmetric properties with respect to said optical axis.

7. The method according to claim 1, wherein said second measurement is taken by superimposing said second wave fronts with first reference wave fronts generated by reflecting said first incident beam from a reference surface of said interferometer optics.

8. The method according to claim 1, wherein said third measurement is taken by superimposing said third wave fronts with second reference wave fronts generated by reflecting said second incident beam from a reference surface.

9. The method according to claim 1, wherein said fourth measurement is taken by superimposing said fourth wave fronts with second reference wave fronts generated by reflecting said second incident beam from a reference surface.

10. The method according to claim 1, wherein said first measurement is taken by superimposing said first wave fronts with first reference wave fronts generated by reflecting said first incident beam from a reference surface of said interferometer optics.

11. The method according to claim 10, wherein said optical properties of said interferometer optics substantially correspond to phase differences determined by a formula

$$Wint = 1/2 \ (W2 + W3 + W4 - W5),$$

wherein:

Wint represents said phase differences of said interferometer optics,

W2 represents phase differences determined from said first measurement,

W3 represents phase differences determined from said second measurement,

W4 represents phase differences determined from said third measurement, and

W5 represents phase differences determined from said fourth measurement.

12. The method according to claim 1, wherein said first measurement is taken by superimposing said first wave fronts with fifth wave fronts generated by reflecting said first incident beam from said first surface of said first substrate.

13. The method according to claim 12, further comprising:

arranging said first substrate in said beam path of said first incident beam with said first surface facing towards said first incident beam, and interferometrically taking a fifth measurement of sixth wave fronts generated by reflecting said first incident beam from said first surface; and

wherein said optical properties of said interferometer optics substantially correspond to phase differences determined by a formula

$$W_{int} = 1/2 \ (W1 + Wfr + W3 + W4 - W5),$$

wherein:

Wint represents said phase differences of said interferometer optics,

W1 represents phase differences determined from said fifth measurement,

Wfr represents phase differences determined from said first measurement,

W3 represents phase differences determined from said second measurement,

W4 represents phase differences determined from said third measurement, and

W5 represents phase differences determined from said fourth measurement.

14. A method for processing a substrate having an optical surface, said method comprising:

arranging a first substrate having a first surface and a second surface opposite said first surface in a beam path of a first incident beam with said first surface facing towards said first incident beam, and interferometrically taking a first measurement of first wave fronts generated by reflecting said first incident beam from said second surface of said first substrate;

arranging said first substrate in said beam path of said first incident beam with said second surface facing towards said first incident beam,

and interferometrically taking a second measurement of second wave fronts generated by reflecting said first incident beam from said second surface of said first substrate;

arranging a third surface of a second substrate in a beam path of a second incident beam, and interferometrically taking a third measurement of third wave fronts generated by reflecting said second incident beam from said third surface of said second substrate, while said first substrate is not arranged in said beam path of said second incident beam;

arranging said third surface of said second substrate and said first substrate in said beam path of said second incident beam, and interferometrically taking a fourth measurement of fourth wave fronts generated by reflecting said second incident beam from said third surface and through said first substrate; and

determining deviations of said optical surface from a target shape thereof in dependence of said first, second, third and fourth measurements.

15. The method according to claim 14, wherein said optical surface is said third surface of said second substrate.

16. The method according to claim 15, wherein said determined deviations correspond to calculated deviations substantially determined by a formula:

$$hM = 1/4 \ (-W2 - W3 + W4 + W5) - h_{iM}$$

wherein:

hM   represents said calculated deviations,

W2   represents phase differences determined from said first measurement,

W3   represents phase differences determined from said second measurement,

W4   represents phase differences determined from said third measurement,

W5   represents phase differences determined from said fourth measurement, and

h_{iM} represents a predetermined input offset.

17. The method according to claim 14, wherein said optical surface to be qualified or manufactured, respectively, is said second surface of said first substrate.

18. The method according to claim 17, wherein said determined deviations correspond to calculated deviations substantially determined by a formula:

$$h2 = 1/4 \ (- W2 + W3 - W4 + W5) - h_{i2}$$

wherein:

h2   represents said calculated deviations,

W2   represents phase differences determined from said first measurement,

W3   represents phase differences determined from said second measurement,

W4   represents phase differences determined from said third measurement,

W5   represents phase differences determined from said fourth measurement, and

h_{i2} represents a predetermined input offset.

19. The method according to claim 14, further comprising:

arranging a fourth optical surface of a third substrate in said beam path of said first incident beam, and interferometrically taking a sixth measurement of seventh wave fronts generated by reflecting said first incident beam from said optical surface;

20. The method according to claim 19, wherein said optical surface to be qualified or manufactured, respectively, is said fourth surface of said third substrate.

21. The method according to claim 20, wherein said determined deviations correspond to calculated deviations substantially determined by a formula:

$$h0 = 1/4 \ (-W2 - W3 - W4 + W5 + 2\ W6) - h_{i0}$$

wherein:

$h0$ represents said calculated deviations,

$W2$ represents phase differences determined from said first measurement,

$W3$ represents phase differences determined from said second measurement,

$W4$ represents phase differences determined from said third measurement,

$W5$ represents phase differences determined from said fourth measurement,

$W6$ represents phase differences determined from said sixth measurement, and

h_{i0} represents a predetermined input offset.

22. The method according to claim 14, further comprising arranging said first substrate in said beam path of said first incident beam with said first surface facing towards said first incident beam, and

interferometrically taking a fifth measurement of sixth
wave fronts generated by reflecting said first incident
beam from said first surface.

23. The method according to claim 22, wherein said optical
surface to be qualified or manufactured, respectively,
is said first surface of said first substrate.

24. The method according to claim 23, wherein said
determined deviations correspond to calculated
deviations substantially determined by a formula:

$$h1 = 1/4 (2\ W1 - W2 - W3 - W4 + W5) - h_{i1}$$

wherein:

h1   represents said calculated deviations,

W1   represents phase differences determined from said
fifth measurement,

W2   represents phase differences determined from said
first measurement,

W3   represents phase differences determined from said
second measurement,

W4   represents phase differences determined from said
third measurement,

W5   represents phase differences determined from said
fourth measurement, and

h_{i1} represents a predetermined input offset.

25. The method according to claim 14, wherein said first
measurement is taken by superimposing said first wave
fronts with fifth wave fronts generated by reflecting
said first incident beam from said first surface of
said first substrate.

26. The method according to claim 25, further comprising arranging said first substrate in said beam path of said first incident beam with said first surface facing towards said first incident beam, and interferometrically taking a fifth measurement of sixth wave fronts generated by reflecting said first incident beam from said first surface.

27. The method according to claim 26, wherein said optical surface to be qualified or manufactured, respectively, is said first surface of said first substrate and wherein said determined deviations correspond to calculated deviations substantially determined by a formula:

$$h1 = 1/4 \ (W1 - Wfr - W3 - W4 + W5) - h_{i1}$$

wherein:

h1   represents said calculated deviations,

W1   represents phase differences determined from said fifth measurement,

Wfr   represents phase differences determined from said first measurement,

W3   represents phase differences determined from said second measurement,

W4   represents phase differences determined from said third measurement,

W5   represents phase differences determined from said fourth measurement, and

h_{i1} represents a predetermined input offset.

28. The method according to claim 26, wherein said optical surface to be qualified or manufactured, respectively, is said second surface of said first substrate and wherein said determined deviations correspond to

calculated deviations substantially determined by a formula:

$$h2 = 1/4 \ (- W1 - Wfr + W3 - W4 + W5) - h_{i2}$$

wherein:

$h2$ represents said calculated deviations,

$W1$ represents phase differences determined from said fifth measurement,

Wfr represents phase differences determined from said first measurement,

$W3$ represents phase differences determined from said second measurement,

$W4$ represents phase differences determined from said third measurement,

$W5$ represents phase differences determined from said fourth measurement, and

h_{i2} represents a predetermined input offset.

29.   The method according to claim 26, wherein said optical surface to be qualified or manufactured, respectively, is at least one of said first surface of said first substrate and said second surface of said first substrate and wherein said determined deviations correspond to calculated values substantially determined by a formula:

$$D = 1/2 \ (W5 - W4 - Wfr) + hi$$

wherein:

D represents said calculated values,

Wfr represents phase differences determined from said first measurement,

$W4$ represents phase differences determined from said third measurement,

$W5$ represents phase differences determined from said fourth measurement, and

hi   represents a predetermined input offset.

30. The method according to claim 25, wherein said optical surface to be qualified or manufactured, respectively, is at least one of said first surface of said first substrate and said second surface of said first substrate and wherein said determined deviations correspond to calculated values substantially determined by a formula:

$$i = n \cdot (W_5 - W_4) - (n - 1) \cdot W_{fr}$$

wherein:

i   represents said calculated values,

Wfr   represents phase differences determined from said first measurement,

W4   represents phase differences determined from said third measurement,

W5   represents phase differences determined from said fourth measurement, and

n   represent an average index of refraction of a material of said first substrate.

31. The method according to claim 14, further comprising:

    (j) machining said optical surface in dependence of said determined deviations.

32. The method according to claim 31, wherein said machining is only performed if said deviations exceed a predetermined threshold.

33. The method according to claim 31, wherein said determining of deviations and said machining are repeatedly performed.

34. The method according to claim 31, further comprising a finishing of said optical surface.

35. The method according to claim 34, wherein said finishing comprises applying a coating to said optical surface.

36. The method according to claim 35, wherein said coating comprises at least one of a reflective coating, an anti-reflective coating and a protective coating.

37. The method according to claim 14 wherein processing the substrate comprises manufacturing the substrate.

38. The method according to claim 14 wherein processing the substrate comprises qualifying the substrate.

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Abstract

A method for qualifying and/or manufacturing an optical surface includes:

arranging a first substrate having a first surface and a second surface opposite the first surface in a beam path of a first incident beam with the first surface facing towards the first incident beam, and taking an interferometric measurement of the second surface;

arranging the first substrate in the beam path of the first incident beam with the second surface facing towards the first incident beam, and taking an interferometric measurement of the second surface;

arranging a third surface of a second substrate in a beam path of a second incident beam, and taking an interferometric measurement of the third surface;

arranging the third surface of the second substrate and the first substrate in the beam path of the second incident beam, and taking an interferometric measurement of the third surface.